HAND-AX was one of the earliest technological innovations. This specimen, shown slightly larger than actual size, was found at Saint-Acheul in France. It is approximately 200,000 years old. The hand-ax was photographed at the American Museum of Natural History.

Innovation in Technology

It is through technological innovations that science is brought to bear upon man's material existence. The difference between creative science and creative technology is chiefly one of motive

by John R. Pierce

Technological innovations have been as important as language, art and science in distinguishing man from beast. And although technological innovation antedates our species, it has never before occupied so great a share of man's energies.

Our works are built on old foundations—on obsolete inventions such as the hand-ax and the bow no less than on inventions that have survived, such as agriculture and the wheel. But during most of human history technological art accumulated gradually. Up to a few hundred years ago the techniques of civilized life had scarcely advanced beyond the best achievements of the ancients. Then our control over the forces of nature began to increase at an explosive rate.

We usually think of our contemporary world as the product of science. The relationship between science and technology is certainly very close, and neither could have attained its present state without the other. But it is technology that affects us directly. Some of the greatest scientific innovations, for example, the discoveries of astronomy and the theory of evolution, have had little influence on our material existence. Even electromagnetic theory and atomic physics had no impact until they were brought to bear on technology by people who were not content with understanding, but who wanted to change our way of living and of doing things.

In this article we shall examine some recent advances to see what light they throw on the creative process in the complex technology of today. What do we mean by a technological innovation? Surely not the tail fins on this year's automobile, nor a new catch on a refrigerator door. A true innovation must perform some important function. It may do a wholly new job or do an old job far better or far more cheaply than it was done before.

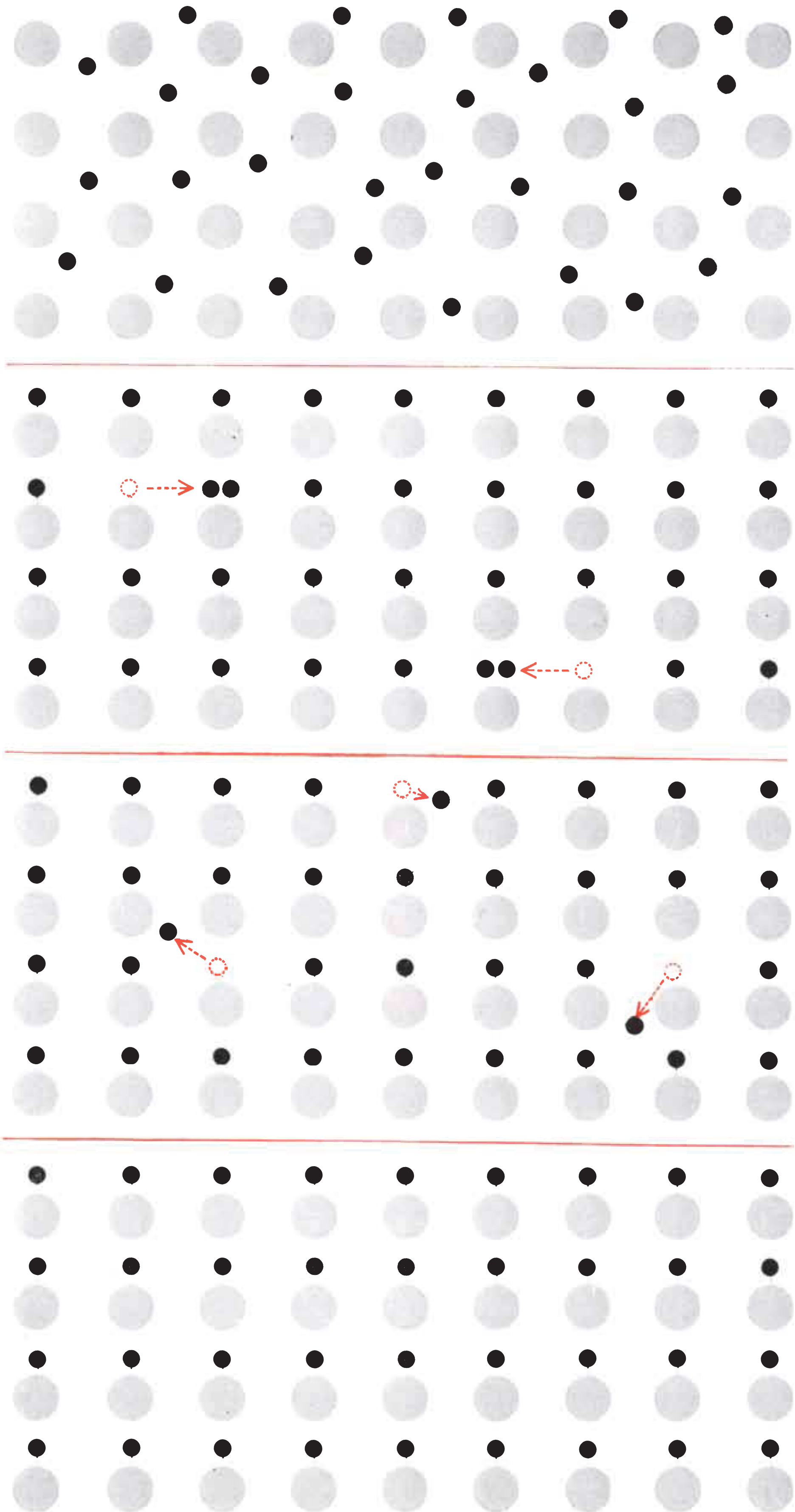
Clearly there are many examples of such innovation. An aeronautical engineer might cite the turbojet engine or the "area rule" for designing supersonic aircraft. A chemist could speak of polyethylene and other useful materials that are made by linking small molecules together into giant ones. A nuclear engineer might mention the breeder reactor. I shall talk about the things I know best: electronic devices. The specific examples are not important. From the facts surrounding a particular innovation we may hope to derive some general lessons about the character of innovation itself.

To get at the facts in the field of technology is usually difficult. Whereas the scientist must publish his results if his contribution is to be recognized, the technologist must get the job done. He may be careless about publication; he may even withhold information. Furthermore, there are probably more people working competitively on technological than on scientific problems. Thus the chance of simultaneous discovery is perhaps greater in technology than in science. An innovation is no less legitimate for having two fathers, but it is troublesome for the historian. For these reasons I shall discuss some reasonably noncontroversial innovations made at the Bell Telephone Laboratories, where I am employed, under circumstances which I believe I understand.

I have chosen my examples to illustrate different aspects of the interaction between science and technology. In one case the technological problem helped open a wide field of physical research, and the invention itself depended on a great advance in fundamental knowledge. In another the underlying physical laws were already known. The innovation lay in finding a new way to apply known physical phenomena. Finally I shall describe the origin of a complex system which combined existing techniques, new scientific knowledge and new devices.

The first example, which has probably already occurred to the reader, is the transistor. Let us sketch in its background. To begin with there was a need, an important function to perform. The vacuum tube, through its ability to amplify minute signals, had made possible the wonderful arts of radio and long-distance telephone transmission. But even before World War II Ralph Bown, then director of radio research at Bell Laboratories, had pointed out two weaknesses of ordinary vacuum tubes. First, they cannot amplify a very broad band of frequencies. This defect was later remedied by the device known as the traveling-wave tube. Second, they waste energy: the power needed to operate a vacuum tube is often thousands or millions of times greater than the power of the signals it amplifies. It is this weakness that the transistor finally overcame.

The invention of the transistor turned out to require new physical principles, new knowledge of nature. Nowadays *The Physical Review* is full of contributions to solid-state physics, but in the pre-transistor period the field was largely neglected. However, a few men at Bell Laboratories decided to take it up. For one thing, solid-state devices such as copper-oxide rectifiers and crystal diodes (the detector in the old "crystal" radio set), were important in telephony. For another, the tools of quantum mechanics had been sharpened to the point at which they could be usefully brought to bear on the properties of sol-



ELECTRICAL CONDUCTORS contain movable charges. In a metallic conductor (*top*) atoms (*gray circles*) have loosely held electrons (*black dots*) which can move through crystal. In *p*-type semiconductor (*second from top*) some atoms capture electrons from their neighbors leaving movable positive "holes" (*dashed circles*). In *n*-type material (*third from top*) some atoms have loose electrons. Insulator (*bottom*) contains no loosely held electrons.

ids. Various capable men were attracted to the field, among them William Shockley and Walter Brattain.

Their early studies were interrupted by the war, but were taken up again afterward with new vigor and by more people. Among the newcomers was John Bardeen, who, with Shockley and Brattain, was to share the Nobel prize for contributions to solid-state physics in connection with the transistor.

The group concentrated much of its attention on semiconducting materials. These are crystals containing a small fraction of impurities. The impurity atoms have one more electron than they need to satisfy the requirements of crystal structure, or one less. In the first case the extra electrons are easily detached, and move through the crystal when acted on by electric forces. Such a crystal is known as an *n*-type semiconductor. In the second case a vacancy may be filled when an electron from a neighboring atom moves over, transferring the deficiency or "hole" to the atom it left. The hole may move again by the transfer of an electron from a second neighboring atom, and so on. This kind of material is called *p*-type. Both kinds conduct electricity, but not in the way that ordinary conductors do [*see illustrations at left*].

At a series of conferences in 1946 it was decided to make a thorough study of silicon and germanium, the simplest of semiconductors, under the general direction of Shockley. Altogether as many as 13 physicists, chemists and engineers in various departments of Bell Laboratories participated in the work in some essential way. They prepared highly purified samples of the materials and studied their bulk and surface properties. The investigators were not a closely organized and firmly directed "team"; they were talented individuals working on matters of great personal, as well as mutual, interest.

Shockley was not only interested in the general behavior of silicon and germanium; he also wanted to make a semiconductor amplifier. He had an idea of how it might be done. If one can vary the resistance of a material, one can control the current flowing through it, and so produce an amplified electric signal. Now the resistance of a material such as silicon or germanium decreases as its content of free electrons increases. Shockley reasoned that the number of electrons in a very thin film of silicon could be substantially changed by applying strong electric fields which would either attract electrons into the film or repel them. If so, varying the field

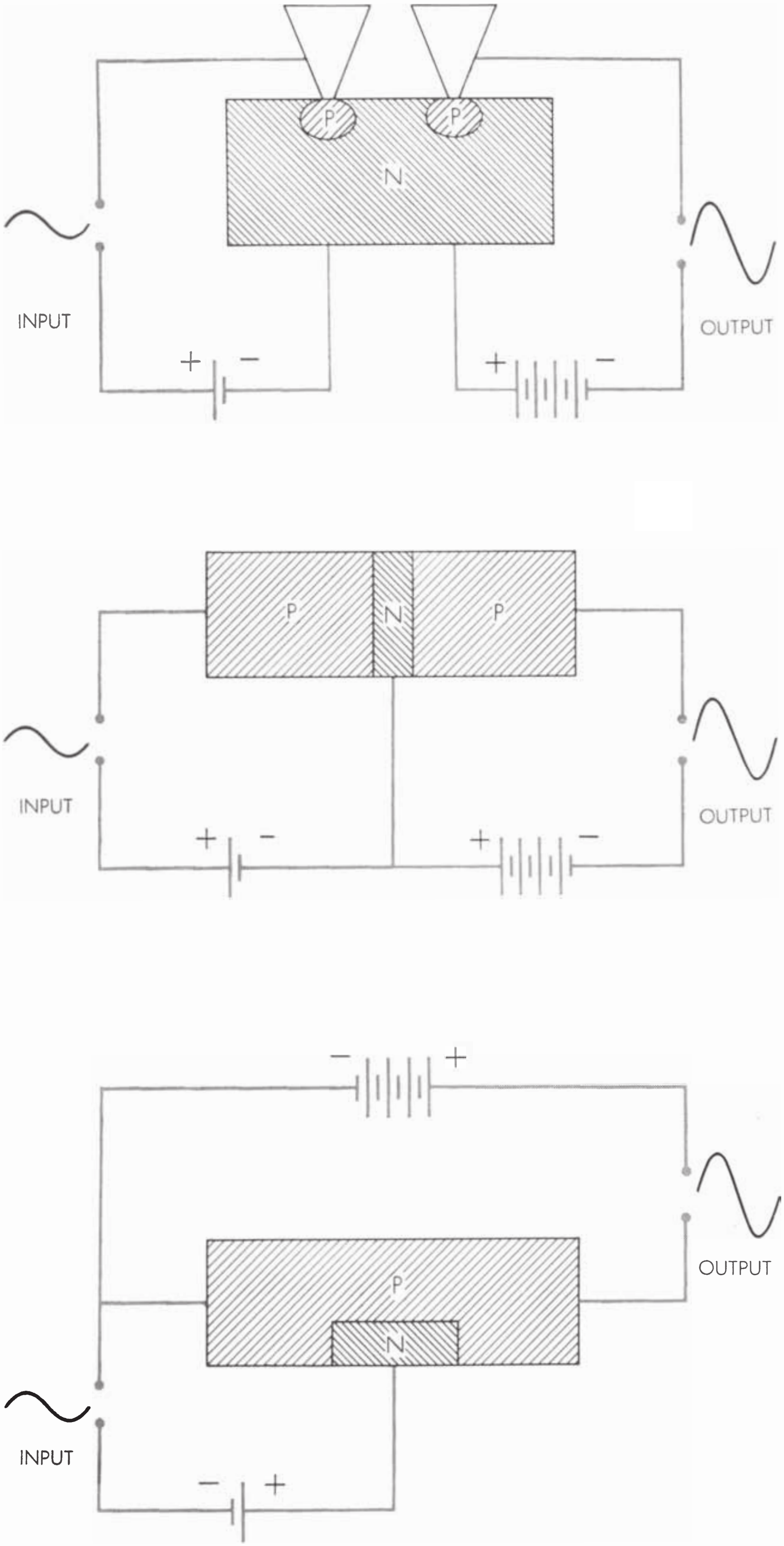
should vary the resistance of the film and hence the current flowing through it.

Efforts to make such a device did indeed lead to a solid-state amplifier, but one of a quite different sort. In the first experiments it turned out that a strong electric field had no effect on the resistance of a silicon film. Bardeen then proposed that the electrons affected by the field were not free inside the silicon, but were trapped at the surface of the material in what he called "surface states." Here was not only a practical difficulty but a new and important physical phenomenon. There followed a great variety of fundamental experiments on surface states. In some of them solid blocks of silicon were immersed in a conducting liquid to which various voltages were applied. This method actually produced some amplification of the sort predicted by Shockley, but it also led to the discovery of another and even more important fact.

In experiments on the immersed surface of a block of *n*-type germanium (in which conduction is mediated by electrons) there appeared to be a flow of holes near the surface. While following up this unexpected result, Bardeen suggested using germanium with metallic electrodes rather than liquids. Experimenting with such an arrangement, Brattain discovered a new effect: When two pieces of *p*-type material are separated by a body of *n*-type, and the proper voltages are applied to the three sections, holes will flow from one *p*-type layer to the other, passing completely through the *n*-type material. This effect, now called transistor action, was a new and important physical phenomenon. It also provided the key to the solid-state amplifier, for by varying the voltage of the *n*-type layer it is possible to control the flow of holes from a *p*-type "emitter" region into and through the *n*-type "base" region and on to a *p*-type "collector" region.

Thus was born the point-contact transistor. It filled the original need: it consumes very little power. Furthermore, it is smaller than the vacuum tube. Point-contact and later types of transistors have given us not only pocket radios and eyeglass hearing-aids, but complex electronic computers and other electronic gear that can be carried in airplanes or stowed in a manhole rather than in a telephone building.

In the history of the transistor we have the happiest combination of fundamental physical investigation and technological innovation. A group of men with related interests were working in a new field of science—the physics of the solid



TYPES OF TRANSISTORS are diagrammed schematically. Point-contact transistor (*top*) and junction transistor (*middle*) shown here are called "*p-n-p*" because they are made of two pieces of *p*-type material separated by a layer of *n*-type. There is also an "*n-p-n*" version of each type. Field-effect transistor (*bottom*) is a more recent development, although it was this kind of device that the inventors of the transistor were at first trying to discover.

state. They had two motives: to learn something, and to make a new and better amplifier. The need for the amplifier helped to stimulate the work. The theoretical tools of quantum mechanics were available to make it possible. But the irreplaceable element was the men themselves. Yet, while insight and invention are the products of individual minds, individuals are most effective when they work together in a field that is neither so narrow as to preclude adventure nor so broad as to scatter energies and prevent a fruitful interchange of ideas.

Finally we should note that the transistor work has given a still-increasing impetus to both science and technology. We now have more semiconductor devices, such as junction diodes, junction transistors, and field-effect transistors somewhat different from those which Shockley originally envisioned. Interest in solids has extended to other types, including photoconducting, ferromagnetic and ferroelectric materials. These too are finding important applications in electronics. And solid-state physics itself has become highly attractive to able physicists in universities as well as in industrial laboratories.

The second innovation I shall discuss is the negative-feedback amplifier, whose functions or principles are hidden away in almost all electronic devices and equipment. The principle of negative feedback underlies all electronic control. We shall see how we owe to it the high quality and low cost of modern long-distance telephone transmission.

Like the transistor, the idea of negative feedback was a response to a need for better amplifiers. In this case, however, the invention did not require new physical knowledge. A single creative effort showed how to apply known devices in a new and superior way.

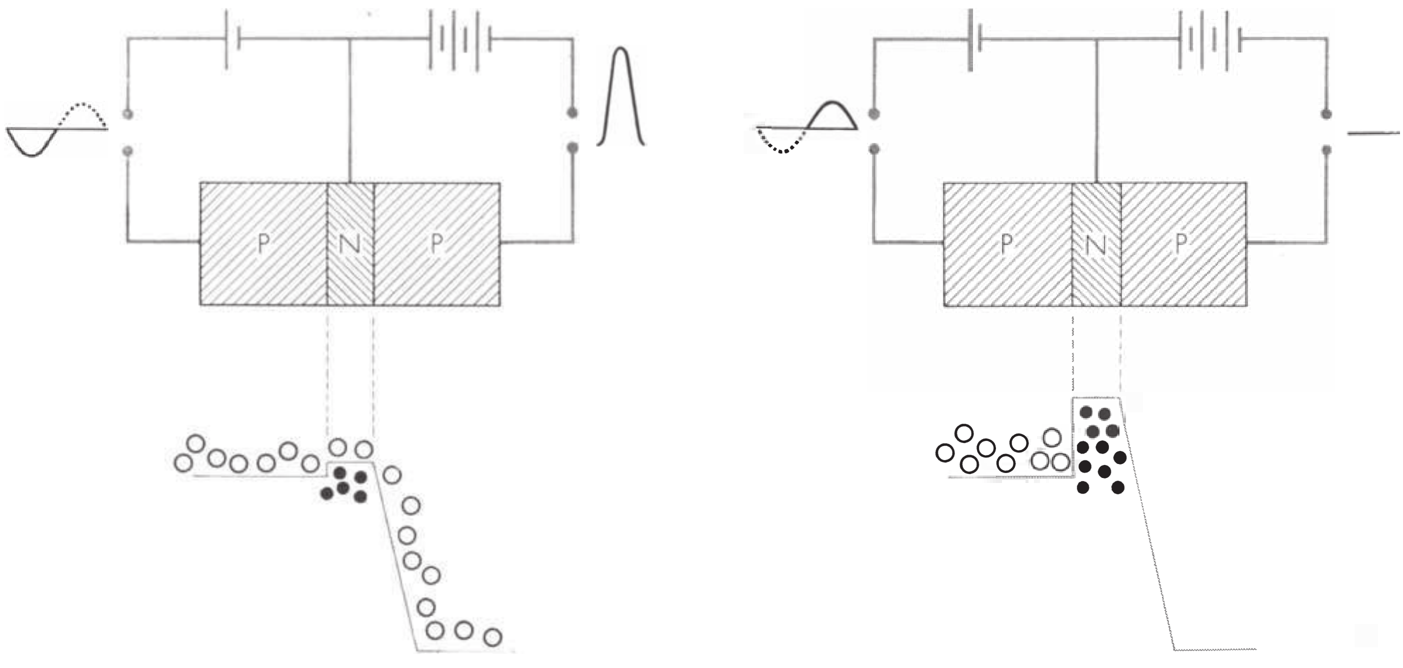
The story again goes back to the first vacuum-tube amplifiers. Inserted at intervals along a telephone line to boost the power of weakened signals, they made it possible to send messages over really long distances. In the beginning a pair of wires and a series of amplifiers could accommodate only one conversation at a time. Then, in the 1920s, telephone engineers learned to put several simultaneous messages on the same pair of wires and through the same amplifiers by sending them at different frequencies. This is the method used to transmit different radio programs through the same space at the same time. However, in radio broadcasting only one program at a time goes through a given transmitter or receiver. In today's telephone circuits hundreds of conversations go through one amplifier at a time.

To keep the signals from mixing with each other and becoming distorted, we need an extremely good amplifier. It must be linear; that is, the strength of the output signal must be strictly proportional to the strength of the input signal. Also it must be stable, maintaining the same amplification at all times. Vacuum tubes are inherently neither linear nor stable. In the 1920s engineers had all they could do to make amplifiers good enough to amplify a few telephone conversations a few times. Today we can send 1,800 separate messages through more than 1,000 successive amplifiers without noticeable distortion. It is negative feedback that is responsible for this improvement.

The principle is simple: Feedback means just what the word implies. A part of the output of an amplifier is fed back to the input side and mixed with the incoming signal before it is amplified. If the two are mixed in such a way that the portion fed back adds to the incoming signal, we have positive feedback. It increases the net input to the amplifier and thus increases the over-all gain. With enough positive feedback the amplifier can supply all the necessary input, and becomes an oscillator which generates its own signal.

If the mixing subtracts the energy fed back from the incoming signal, the net input decreases and the over-all gain is reduced. All the advantages that have come from the innovation depend on this seemingly unpromising fact.

It turns out that if the proportions are chosen properly, the actual gain of the arrangement depends almost entirely on the fraction of the output signal fed



TRANSISTOR ACTION, which is responsible for the amplifying ability of transistors, involves the flow of positive holes (*open circles*) through a layer of *n*-type material containing movable electrons (*black dots*). At left the input signal, shown as a sine wave, charges the layers so that the *n*-type material allows the passage of many holes. This results in a large output (*tall wave at other side of circuit*). At right the signal reverses and the *n*-type layer forms an impassable barrier to holes. There is no output on this half-cycle.

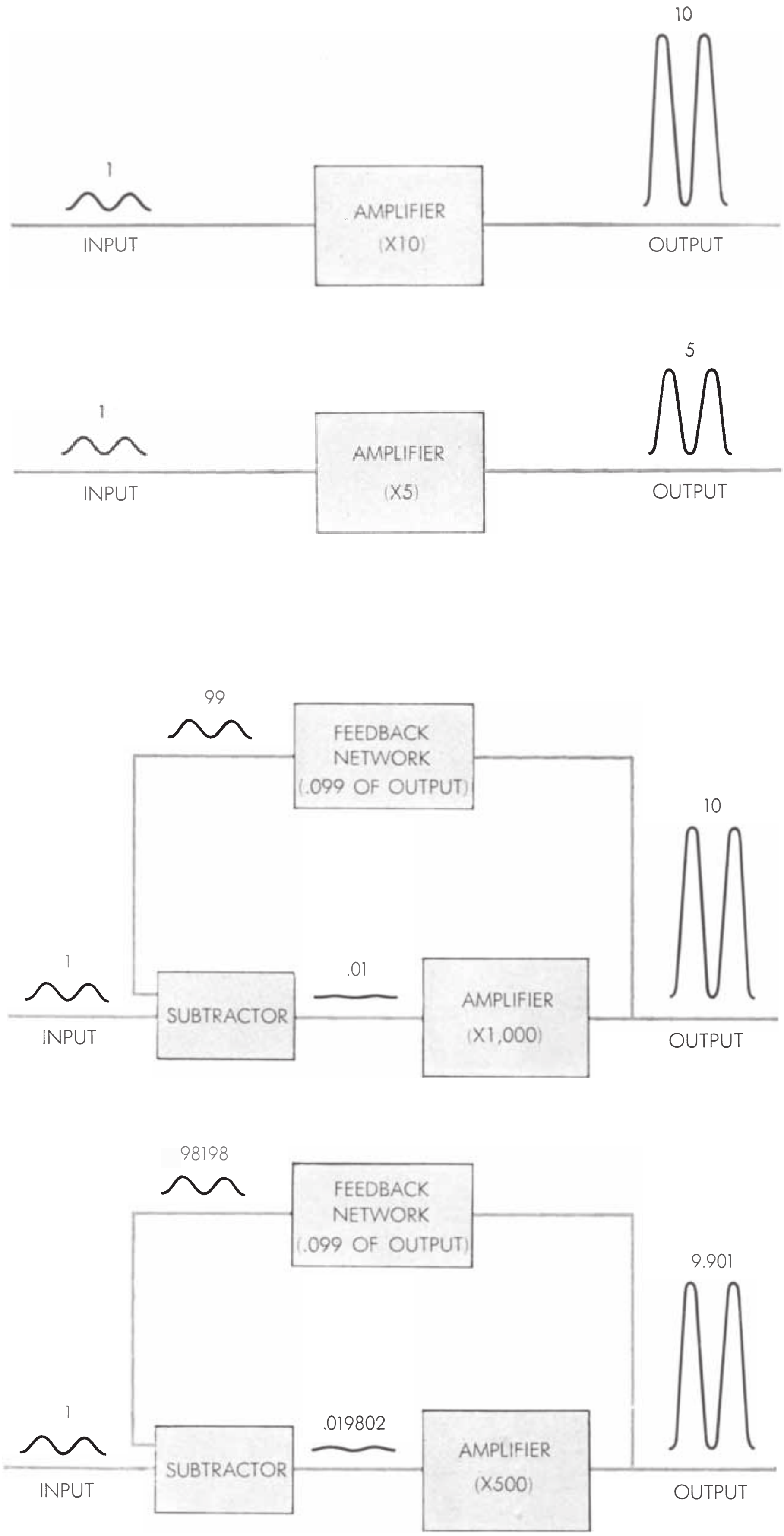
back, and not on the intrinsic gain of the amplifier. For example, suppose the gain without feedback is 1,000 times, and a fraction of the output just under one tenth is fed back and subtracted. Then the net gain will be 10 [*see illustration at right*]. Now if the intrinsic gain drops to as low as 500, but the same fraction of the output is fed back, the net gain is still almost exactly 10. Thus the gain is set not by nonlinear vacuum tubes, but by linear and stable elements—resistances, condensers and coils—which determine the fraction of the output that is fed back and subtracted from the input signal.

How did this innovation come about? A number of Bell Laboratories engineers, among them Harold S. Black, had been trying for several years to make amplifiers capable of handling many messages at once. The physical ingredients and mathematical tools needed for the invention were all at hand. All that was lacking was the idea. One day in 1927 it came to Black while he was going to work on the Lackawanna Ferry. He immediately began to work out the details on the margin of his morning newspaper.

This, of course, was only the beginning of the story. The full exploitation of Black's idea required many years of research by a number of workers. And like the transistor it opened the field for important discoveries by others and for applications ranging from hi-fi to missiles. It also provided a popular field of study in universities and industrial laboratories. But essentially the negative-feedback amplifier was the creation of a single mind.

As our final example of innovation in technology let us consider briefly the microwave-relay system which carries telephone conversations and television programs across the country without the use of cables. The key word here is "system." The problem was not to make a particular device, but to weld a great number of devices into a complex whole. Some of the devices were available at the start; others had to be developed. But the chief innovation was the choice, among the many alternative methods and devices, of the best combination of methods and devices—the system as a whole, and not merely its separate parts.

Work on the microwave relay was begun at Bell Laboratories shortly after World War II, under the direction of Harald T. Friis. Research before the war and radar work during the war had pro-



NEGATIVE FEEDBACK stabilizes the gain of an amplifier. Without feedback (*top diagrams*) the output of an amplifier changes in the same proportion as its gain. With negative feedback (*bottom diagrams*) a decrease in gain is compensated by an increase in the net signal fed to the amplifier proper so that over-all gain of system remains essentially constant.

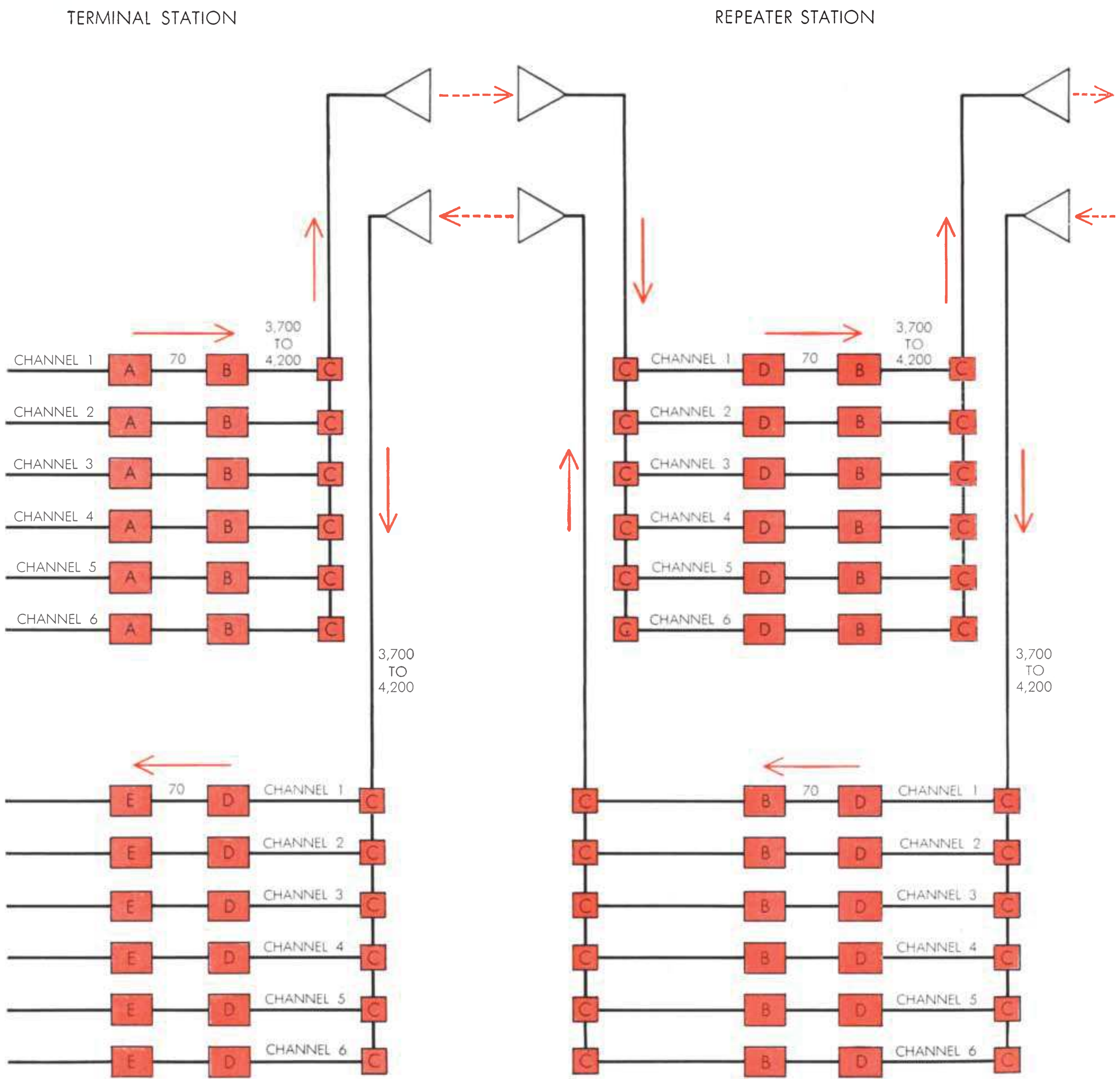
vided a considerable fund of knowledge about microwaves, and a good deal of sophisticated equipment. But more knowledge and better equipment were needed for the job.

For instance, it was known that microwaves, like light, travel in straight lines, so that each relay point must be on a line of sight to the next. But by how much must the line-of-sight path clear the ground? And how would atmospheric disturbances affect the beam?

While some engineers investigated such questions, others were busy designing new devices: microwave amplifiers capable of handling hundreds of telephone signals, a new type of antenna, filters to sort out signals of different frequencies, and many others.

Friis and his colleagues had dozens of important decisions to make. To name only one, what frequency should be used? At a high frequency, say 4,000 megacycles, antennas have narrow beams, so that a large fraction of the power transmitted from one relay station would reach the receiver of the next. At 2,000 megacycles the beams are much broader and more power would be wasted. On the other hand, tubes that operated satisfactorily at 2,000 megacycles were already available. If the higher frequency were decided on, new tubes would have to be designed and manufactured.

Friis's main problem, then, was not to



MICROWAVE TRANSMISSION SYSTEM for television programs is diagrammed schematically. Terminal station (*left*) feeds signals to and from local TV transmitters. Repeater station (*right*) boosts power as signals travel across the country. Output of a local transmitter is converted to 70 megacycles in circuits A, amplified and converted to carrier frequency between 3,700 and 4,200 megacycles in B and fed to antenna through filters C, each of which passes the frequency of a single channel. Relayed signal is converted to 70 megacycles for re-amplification in D. Circuits E convert signal to the appropriate frequency for the local transmitter.

invent this gadget or that, but to choose the best course, technically and economically, among a bewildering array of possibilities. The art of making such a choice is usually called systems engineering when the alternative means and the required knowledge are all at hand. When they are not, I suppose it should be called systems research. By 1948 the results of the research of Friis and his colleagues had been embodied in an experimental system which was installed between New York and Boston. This was the prototype of the transcontinental microwave system, which was put into service in 1951.

What can we learn from these examples? First, that in technology, as in science, the individual act of creation is the essential ingredient of innovation. It

RELAY STATION at Mount Rose in Nevada is photographed from the air. At an elevation of 10,076 feet this station is the highest in the national network. On the roof of the building can be seen the specially shaped antennas developed for use in the relay system.

may be an act of creative imagination, as in the case of the negative-feedback amplifier, or an act of creative observation of nature, as in the case of the transistor.

We may, however, observe that, while great innovations in mathematics and science are overwhelmingly more important than small innovations, a small but apt technological innovation may bring widespread and important rewards, not only to the innovator, but to all men.

The creative process in technology certainly seems to take talent, preparation, good judgment in sorting the valuable from the elaborate, incubation, inspiration and verification. Henri Poincaré has cited these elements in connection with mathematical creativity; they are clearly not unique to technology. Certainly the chief difference between scientific and technological innovation is one of motive. Scientists seek new knowledge; technologists seek to do something useful.

This difference in motive is reflected in the source of innovation. The direction of a scientist's work is likely to be determined by current fashion, and this assures the required association with and stimulation from others working on related problems. The broad goals of the technologist are usually set by the objectives of an organization rather than by fashion.

Without a clear and understandable goal, effort will be diffuse and pointless, for without a goal there is no telling success from failure. But, if the exact course or approach as well as the goal is specified, there is no real room for technological innovation. The attack on scientific or technological problems must be led with full freedom by men who are both professionally competent and creative themselves.

Useful innovations are made in small and specialized organizations as well as in large ones. But the broad yet clear objectives of a large organization, however, allow the support of the sort of mathematical and scientific research which can form the basis of major technological innovations. Indeed, such support of mathematics and science is absolutely essential if we are to escape from the narrow range of that which is currently fashionable in science and explore equally rewarding areas toward which our attention is directed by human needs.

We need both creative scientists who are broad enough to look beyond the current fashions and creative engineers who can appreciate scientific discoveries and incorporate them into technology.